



Hydroxylase inhibition regulates inflammation-induced intestinal fibrosis through the suppression of ERK-mediated TGF- β 1 signaling

Cabrero Manresa, M., Tambuwala, M. M., Radhakrishnan, P., Harnoss, J. M., Brown, E., Cavadas, M. A., Keogh, C. E., Cheong, A., Barrett, K. E., Cummins, E. P., Schneider, M., & Taylor, C. T. (2016). Hydroxylase inhibition regulates inflammation-induced intestinal fibrosis through the suppression of ERK-mediated TGF- β 1 signaling. *AJP - Gastrointestinal and Liver Physiology*, 311(6), G1076-G1090.
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1 **Hydroxylases regulate intestinal fibrosis through the suppression**
2 **of ERK mediated TGF- β 1 signaling**

3 ^{1,2}Mario C. Manresa, ³Murtaza M. Tambuwala, ⁴Praveen Radhakrishnan, ⁴Jonathan M.
4 Harnoss, ¹Eric Brown, ^{1,5}Miguel A. Cavadas, ¹Ciara E. Keogh, ^{1,5}Alex Cheong, ⁶Kim E.
5 Barrett, ¹Eoin P. Cummins, ⁴Martin Schneider and ^{1,5}Cormac T. Taylor.

6 ¹School of Medicine and Medical Science, UCD Conway Institute, University College
7 Dublin, Belfield, Dublin 4, Ireland. ²School of Medicine and Medical Science, Charles
8 Institute of Dermatology, University College Dublin, Belfield, Dublin 4, Ireland. ³School of
9 Pharmacy and Pharmaceutical Science, Ulster University, Coleraine, County Londonderry
10 BT52 1SA, Northern Ireland. ⁴Department of General, Visceral and Transplantation Surgery,
11 University of Heidelberg, Im Neuenheimer Feld 110, Heidelberg, 69120, Germany. ⁵Systems
12 Biology Ireland, University College Dublin, Belfield, Dublin 4, Ireland. ⁶Department of
13 Medicine and Biomedical Sciences Ph.D. Program, University of California, San Diego,
14 School of Medicine, La Jolla, CA 92093, USA

15 **Running head:** Hydroxylase inhibition suppresses fibrosis

16 **Corresponding author:** Cormac T Taylor, UCD Conway Institute, University College
17 Dublin, Belfield, Dublin 4, Ireland. Email: Cormac.Taylor@UCD.ie. Tel: +353 1-716-673.
18 Fax: +353 1-716-6701.

19

20

21 **Abstract**

22 Fibrosis is a complication of chronic inflammatory disorders such as
23 inflammatory bowel disease (IBD), a condition which has limited therapeutic
24 options and often requires surgical intervention. Pharmacologic inhibition of
25 oxygen-sensing prolyl hydroxylases (PHD), which confer oxygen-sensitivity
26 upon the hypoxia inducible factor (HIF) pathway, has recently been shown to
27 have therapeutic potential in colitis, although the mechanisms involved remain
28 unclear. Here, we investigated the impact of hydroxylase inhibition on
29 inflammation-driven fibrosis in a murine colitis model. Mice exposed to dextran
30 sodium sulfate followed by period of recovery developed intestinal fibrosis
31 characterized by alterations in the pattern of collagen deposition and infiltration
32 of activated fibroblasts. Treatment with the hydroxylase inhibitor
33 dimethyloxalylglycine (DMOG) ameliorated fibrosis. TGF- β 1 is a key regulator
34 of fibrosis which acts through the activation of fibroblasts. Hydroxylase
35 inhibition reduced TGF- β 1-induced expression of fibrotic markers in cultured
36 fibroblasts suggesting a direct role for hydroxylases in TGF- β 1 signalling. This
37 was at least in part due to inhibition of non-canonical activation of extracellular
38 signal-regulated kinase (ERK) signalling. In summary, pharmacologic
39 hydroxylase inhibition ameliorates intestinal fibrosis, through suppression of
40 TGF- β 1-dependent ERK activation in fibroblasts. We hypothesize that in
41 addition to previously reported immunosuppressive effects, hydroxylase
42 inhibitors independently suppress pro-fibrotic pathways.

43 **New and noteworthy**

44 Here we show that hydroxylase inhibitors reduce fibrosis associated with
45 intestinal inflammation in vivo. At the cellular level, our data suggest a new
46 HIF independent role of hydroxylase inhibition in the regulation of TGF- β 1
47 signalling. These data also suggest that non-canonical ERK signalling pathway
48 is regulated by hydroxylase inhibition. Together, our results show the
49 therapeutic potential of hydroxylase inhibitors for the treatment of intestinal
50 fibrosis.

51 **Keywords**

52 Hypoxia; Inflammatory bowel disease; Intestinal fibrosis; Hydroxylase
53 inhibition; Transforming growth factor β 1 (TGF- β 1) signalling.

54

55 **Introduction**

56 Intestinal fibrosis is a debilitating complication of inflammatory bowel disease
57 (IBD)(16, 19, 58). Most approaches to therapeutic intervention in IBD are
58 focused on the control of inflammation rather than fibrosis(58). However,
59 surgical intervention is commonly necessary due to the formation of fibrotic
60 tissue(58, 63). Therefore, there is an unmet clinical need for therapies that
61 suppress pro-fibrotic pathways in IBD.

62 Fibrosis occurs as a result of an overactive wound healing response and is
63 characterized by excessive deposition of extracellular matrix (ECM)(16, 47,
64 58). Fibrosis is a complication of multiple chronic inflammatory disorders
65 including chronic kidney disease(12, 55), interstitial lung disease(1, 79) and
66 chronic liver disease(38, 50) as well as IBD(16, 19, 81). At a cellular level,
67 fibrosis occurs as the result of the over-activation of fibroblasts and other ECM-
68 producing cells(1, 12, 16, 79). Among the factors regulating fibrosis,
69 transforming growth factor- β 1 (TGF- β 1) is the key regulator of healing
70 responses that is implicated in most fibrotic disorders(10, 16, 19, 38). The
71 interaction of TGF- β 1 with its cognate receptors on fibroblasts activates
72 canonical (Smad-mediated) and non-canonical (Mitogen Activated Protein
73 Kinases (MAPK)-mediated) signalling pathways that lead to the differentiation
74 of fibroblasts into pro-fibrotic myofibroblasts(10). Through these pathways,
75 TGF- β 1 induces the expression of crucial pro-fibrotic genes such as α -smooth

76 muscle actin (α -SMA), collagen and matrix metalloproteinases and stimulates
77 fibroblast migration to wounded tissue.

78 Hydroxylases are oxygen sensing enzymes which confer hypoxic sensitivity
79 upon the hypoxia inducible factor (HIF) pathway. Four HIF hydroxylases have
80 been identified to date. Three of these are prolyl hydroxylases (termed PHD1-3)
81 which regulate HIF stability, and the fourth is an asparagine hydroxylase,
82 termed factor inhibiting HIF (FIH), that controls HIF transcriptional activity.
83 The PHD2 isoform is the main regulator of HIF stability through targeting HIF-
84 α subunits for hydroxylation-dependent proteosomal degradation(7). These
85 enzymes have also been identified as key players in inflammatory responses(13,
86 20, 53, 61). Hydroxylase inhibitors have recently been found to be well
87 tolerated in patients in clinical trials for efficacy in anemia(9, 28). These
88 compounds have also been found to ameliorate inflammation in multiple animal
89 models of colitis(14, 15, 22, 36, 60, 64). However, it remains unclear whether
90 the protective effects of these drugs extend to the amelioration of intestinal
91 fibrosis. Furthermore, it is also unclear if their protective effects in colitis are
92 dependent on the regulation of HIF or other pathways(36, 60, 61, 64). Moreover
93 recent studies have highlighted a potentially important role for PHD-2 in the
94 regulation of wound healing responses(32, 78, 80).

95 In this study, we investigated the effects of hydroxylase inhibition on the
96 development of intestinal fibrosis. Developing our understanding of the

97 mechanisms underpinning the protective effects of hydroxylase inhibitors in
98 intestinal inflammatory disease will enhance our understanding of their
99 therapeutic potential.

100

Materials and methods

1. Animal studies

C57BL/6 mice were obtained from Charles River U.K. Prolyl hydroxylase-2 heterozygous knockout mice (PHD2^{+/-}) of the Swiss129 background were provided by Professor Martin Schneider (University of Heidelberg, Germany). These mice have been characterised and used in several previous studies(37, 48). All *in vivo* experiments were performed in compliance with regulations of the Irish Department of Health and approved by the University College Dublin's animal research ethics committee or approved by the ethical commission of the local government (No. G263/14) and carried out at the Interfaculty Biomedical Faculty, University of Heidelberg. All experiments were carried out according to the federation of laboratory animal Science association (FELASA) guidelines. Female and male mice (ages 10-12 weeks) were used. For induction of fibrosis, mice were exposed to 2.5% or 5% DSS (MP Biomedicals, Solon, OH, U.S.A) in drinking water for five days. On day 6 mice were switched to normal drinking water and allowed to recover for 8 or 14 days as indicated. During this period, mice were treated with 8mg/mouse DMOG (i.p) every 48 hours.

2. *In vitro* experiments

Primary human colonic fibroblasts (CCD-18Co) were purchased from the American Type Culture Collection (ATCC, LGC Standards, Middlesex, UK). Immortalized mouse embryonic fibroblasts (MEF) were a kind gift from Dr Alexander Hoffmann (University of California, Los Angeles, U.S.A). Primary MEF of both wild type (WT) and PHD-2^{+/-} backgrounds were isolated from murine foetuses of the appropriate background. All cells were grown in 1X Dulbecco's Modified Eagle's Medium (Thermo Fisher Scientific, Waltham, MA, U.S.A) containing 4.5 g/l glucose and L-glutamine. The medium was supplemented with 10% foetal bovine serum, 50u/ml penicillin and 50 mg/ml streptomycin. In the case of primary MEFs, the medium was also supplemented with 2mM L-glutamine. For CCD-18Co cells, 0.1mM non-essential amino acids were added. For all experiments, cells were switched to serum free medium 24 hours prior to treatment. All treatments were performed in serum free medium. Cells were stimulated with TGF- β 1 for the indicated time periods to induce expression of fibrotic markers and activation of TGF- β 1-stimulated signalling pathways. To investigate the effects of hydroxylase inhibition on TGF- β 1 mediated responses, cells were treated with DMOG or JNJ1935 for 1 or 8 hours prior to TGF- β 1 stimulation as indicated. Hypoxia was achieved in a hypoxia chamber (Coy laboratories, Grass Lake, MI, USA). Steady-state atmospheric levels of oxygen inside the chamber were reduced to 1%, at a temperature of

37°C with 5% CO₂ (balance N₂) in humidified conditions. Media added to cells during hypoxic exposures was pre-equilibrated to hypoxia overnight. For studies where the effects of hydroxylase inhibitors were compared to MEK inhibitors, cells were treated with the MEK inhibitor PD186416 for 1 hour prior to TGF-β1 stimulation. For studies assessing the involvement of HIF in hydroxylase inhibitor mediated effects on fibrosis, cell were treated with Digoxin or Camptothecin and then treated with DMOG prior to TGF-β1 stimulation.

3. Estimation of disease parameters and histologic analysis

Body weight, presence of blood in feces, and stool consistency/diarrhea were recorded daily for each mouse to determine the disease activity index (DAI). These parameters were scored as previously described(64). On termination of the experiments, mice were sacrificed by cervical dislocation and approximately 1cm from the distal colon was collected, fixed in 10% formalin and embedded in paraffin. 4 μm sections were cut, mounted on slides, deparaffinized with xylene, and rehydrated in a graded series of alcohols. For assessment of tissue inflammation, sections were stained using hematoxylin and eosin (H&E). Images were taken using an Aperio scanscope XT (Aperio technologies, Vista, CA, U.S.A). Tissue inflammation was assessed in a blinded fashion by 2-3 independent experienced observers and expressed as an average between the estimations provided. The score was calculated as previously described(61).

Fibrosis was assessed as changes in the amount and pattern of collagen deposition in the colonic mucosa and submucosa using Picrosirius red staining (0.5g of direct red 80 (Sigma) and 0.5g of fast green (Sigma) in 500 ml of saturated picric acid solution) and images obtained as described above. Tissue collagen was quantified using ImageJ (National Institutes of Health, Bethesda, MD) and a quantification method developed in-house. Briefly, images were separated into different colour channels and the red channel was selected for quantification of Collagen. From images obtained using double polarized microscopy, collagen-I was quantified, whereas from images obtained using transmitted light, the total amount of collagen was quantified. The colour threshold was adjusted to obtain black and white images, where collagen structures appeared in black on a white background. A small square fitting the width of the sub-mucosal area was drawn and the percentage of black vs white was quantified in 6 random areas of the sub-mucosa for each imaged sample. Alternatively, the lamina propria was separated using a drawing tool and total mucosal collagen quantified as the percentage of black over a white background.

To analyse the presence of activated fibroblasts in the colon, immunofluorescent staining for α -SMA was performed using 4', 6-diamidino-2-phenylindol (DAPI) to counterstain nuclei (details on the primary and secondary antibodies can be found in table 1, antibodies list). Quantification of α -SMA

was developed using the total percentage of area tool in ImageJ[®] using a method similar to that described for collagen quantification. Briefly, images were split into color channels and the green channel was selected. The threshold of the signal was adjusted and color filter applied so the green signal appeared as black versus a white background. The total amount of black signal in the mucosal area was quantified using ImageJ.

For assessment of the presence of phospho-ERK positive cells in fibrotic tissues, immunohistochemistry was performed using a specific phospho-ERK primary antibody (details can be found in table 1). The procedure was developed using a Vectastain Elite ABC-kit (Vector Laboratories, CA, U.S.A) following manufacturer's instructions with 3, 3'-Diaminobenzidine (DAB) used as substrate. Haematoxylin was used to counter-stain nuclei.

4. Wound healing assay

MEF cells were grown to confluence in 6 well plates. Once confluent, cells were starved overnight in serum free medium. Monolayers were treated with DMOG for 1 hour. After treatment, monolayers were scratched with a p200 tip to produce a wound, and stimulated with TGF-beta for 24 hours. Cells were then fixed in 4% p-formaldehyde and stained for alpha-SMA as described in the previous section.

204 *5. Western blotting*

205 Whole cell protein lysates preparation and western blot analysis were performed
206 according to previously described methods(15). A full list of the antibodies used
207 can be found in table 1.

208 *6. Quantitative real time polymerase chain reaction*

209 RNA was isolated using trizol based extraction. Complementary DNA was
210 synthesized using standard protocols and quantitative real time polymerase
211 chain reaction carried out as previously described(20). A full list of targets
212 analysed and primers used can be found in table 2.

213 *7. luciferase reporter studies*

214 All transfections were performed following previously described methods(52).
215 For the study of the effects of hydroxylase inhibition on TGF-beta mediated
216 activation of Smad responses, MEF cells were transfected with the luciferase
217 reporter SBE4-Luc which was a gift from Bert Vogelstein (addgene
218 plasmid#16495)(75). To validate the specificity of the reporter, MEF were co-
219 transfected with SBE4-Luc and Smad2 or Smad3 overexpression constructs,
220 and the activation of the luciferase reporter was evaluated. pCMV5B-Flag-
221 Smad3 was a gift from Jeff Wrana (addgene pasmid #11742)(40). pCMV5
222 Smad2-HA was a gift from Joan Massague (addgene plasmid #14930)(25).

223

8. *Statistical analysis*

Graph Pad Prism version 5.0 was used for all statistical analysis. One-way ANOVA followed by a Newman Keuls post-test was used for comparison of multiple groups. Student's t-test was used for individual group comparisons. Differences were considered statistically significant when the p-value was ≤ 0.05 . There was a minimum of 3 experimental replicates per group.

Results

1. DMOG reduces intestinal fibrosis in DSS-induced colitis

Hydroxylase inhibitors have been shown to have beneficial effects in multiple models of experimental colitis although their effect on colitis-associated fibrosis remains unknown(15, 60, 64). Figure 1A shows representative images of mouse colon stained with H&E (reflecting tissue inflammation-upper panels), picrosirius red (reflecting collagen deposition-middle panels) or with immunofluorescence staining for α -SMA (reflecting fibrotic fibroblast infiltration-lower panels). DSS-treatment led to mucosal inflammation, disruption of intestinal structures and submucosal edema which partially recovered following 14 days of natural recovery (Figures 1A). Treatment with the hydroxylase inhibitor DMOG reduced markers of inflammation and significantly accelerated the recovery of disease activity scores (figures 1A, 1B and 1C). Inflammation was associated with the development of fibrosis, reflected by a change in the pattern of collagen deposition characterized particularly by increased submucosal collagen (Figures 1A and 1D, white arrows point areas of higher collagen deposition). A similar pattern of collagen deposition in the submucosa in a model of DSS induced fibrosis has previously been described by Ding and colleagues(17). Fibrosis was also characterized by the presence of infiltrating α -SMA positive fibroblasts in the colonic mucosa (Figures 1A and 1E, white arrows point areas of fibroblast infiltration). Mice treated with DMOG demonstrated reduced inflammation with normal mucosal

structures, an absence of inflammatory infiltrates and a reduction in submucosal edema (figure 1A and 1C). DMOG treatment also reduced and normalized the pattern of submucosal collagen deposition, and reduced infiltration by α -SMA positive fibroblasts (Figure 1A, D and E).

2. Heterozygous deficiency of PHD2 is not protective against DSS induced intestinal fibrosis

PHD2 is the main regulator of HIF- α stability (2, 7, 68). PHD2 has been previously reported to be involved in the regulation of the wound healing response(32, 78, 80). To investigate whether the antifibrotic effects of DMOG in intestinal fibrosis were mediated by regulation of the canonical PHD2/HIF pathway, we compared the development of fibrosis in WT vs PHD2 $^{+/-}$ mice exposed to DSS and allowed to recover for 8 days. Figure 2A shows representative images of mouse colon cross-sections stained with H&E, picrosirius red or immunofluorescence for α -SMA, comparing WT and PHD2 $^{+/-}$ mice. DSS caused colitis in WT mice (Figure 2A, B and D). Furthermore, intestinal inflammation was accompanied by profound fibrosis with formation of α -SMA fibroblast aggregates (Figure 2A and 2E) and increased mucosal and submucosal deposition of collagen (Figure 2A and 2F). As demonstrated previously, WT mice treated with DMOG had significantly reduced DAI scores (Figure 2B) and reduced severity of fibrosis with reduced fibroblast infiltration and mucosal collagen deposition (Figure 2A, 2E and 2F). In contrast to DMOG

285 treated mice, PHD2^{+/-} mice were fully susceptible to DSS induced colitis with
286 severe signs of disease reflected by high DAI scores (Figure 2C), severe
287 inflammation (Figure 2A and 2D) and significant fibrosis (Figure 2A, 2E and
288 2F). These results show that reduced activity of PHD2 alone does not
289 ameliorate intestinal fibrosis, suggesting that the antifibrotic actions of DMOG
290 are likely independent of the inhibition of PHD2 and canonical activation of the
291 HIF pathway.

292 *3. Hydroxylase inhibition directly inhibits TGF- β 1 induced fibroblast*
293 *activation.*

294 In order to investigate whether the effects of hydroxylase inhibition on fibrosis
295 were due to its anti-inflammatory actions or to direct anti-fibrotic effects on
296 fibroblasts, we investigated the effects of hydroxylase inhibitors on TGF- β 1-
297 induced fibroblast activation. As shown in Figure 3A, human colonic CCD-
298 18Co fibroblasts stimulated with 1ng/ml of TGF- β 1 for 48 hours underwent a
299 phenotypic transformation into myofibroblasts, characterised by increased
300 expression of α -SMA stress fibres. Moreover, western blot analysis revealed a
301 TGF- β 1 mediated induction of both α -SMA and collagen-1(α) expression
302 (Figure 3B). Treatment with either DMOG or JNJ1935 prior to TGF- β 1
303 stimulation reduced differentiation of the cells into myofibroblasts as shown by
304 reduced presence of α -SMA stress fibres (Figure 3C). Moreover, a reduction of
305 both α -SMA and collagen-1(α)-1 was observed in cells treated with the

hydroxylase inhibitors prior to TGF- β 1 stimulation (Figure 3D-F). Taken together, these data suggest that the antifibrotic actions of hydroxylase inhibitors may be due to their ability to block TGF- β mediated fibroblast activation. Moreover the fact that JNJ1935, which evokes significantly lower activation of HIF than DMOG, caused an equivalent reduction of fibrotic markers to DMOG further suggests that the effects of DMOG are HIF independent(4).

4. Hydroxylase inhibition does not affect activation of the TGF- β -Smad signalling pathway

To investigate how hydroxylase inhibition suppresses the effects of TGF- β 1, we analysed the effects of hydroxylase inhibitors on activation of the canonical TGF-Smad signalling pathway. To facilitate transfection studies, mouse embryonic fibroblasts (MEF) were used in these experiments. DMOG reduced the number of α -SMA positive MEF that migrated into a wound space under the influence of TGF- β 1 in a wound healing assay, compared to cells that were stimulated with TGF- β 1 in the absence of hydroxylase inhibition (Figure 4A). This effect correlated with the ability of DMOG to significantly reduce TGF- β 1 induced expression of α -SMA mRNA, confirming that hydroxylase inhibitors exert similar effects on TGF signalling in MEF and indicating that such effects are also reflected at the transcriptional level (Figure 4B). We next tested the effect of DMOG on Smad signalling. Stimulation with TGF- β 1 induced

phosphorylation of Smad2 and Smad3 at 30 to 120 minutes (Figure 4C-4E). Treatment with DMOG failed to reduce Smad2 phosphorylation at any time point, although it modestly reduced levels of pSmad3 at 2 hours (figure 4C-4E). The combination of hydroxylase and proteasome inhibition did not further affect the phosphorylation of Smad2/3, confirming that DMOG does not enhance pSmad degradation (Figure 4C-4E). To further analyse the effects of hydroxylase inhibitors on Smad pathway functionality, MEF were transfected with the Smad luciferase reporter SBE4-Luc. This construct incorporates four copies of the Smad binding element (SBE) in its promoter. Co-transfection of MEF with SBE4 and Smad2 or Smad3 overexpression plasmids showed activation of the reporter as expected (Figure 4F), with Smad3 more active than Smad2 in this regards in the absence of TGF- β 1 (Figure 4F). Similarly, TGF- β 1 activated the SBE4-Luc reporter in a time-dependent fashion that was maximal at 8 hours (Figure 4G). However, DMOG did not reverse the effect of TGF- β 1 on Smad-dependent luciferase activity (Figure 4G). Together these results show that the effects of hydroxylase inhibitors on responses to TGF- β 1 are not due to blockade of the canonical Smad signalling pathway.

5. Hydroxylase inhibitors reduce TGF- β 1 dependent activation of the non-canonical extracellular regulated kinase (ERK) signalling pathway

To investigate an alternative explanation for the effects of the hydroxylase inhibitors on TGF- β 1 signalling, we next examined the effects on non-canonical

348 signalling. Amongst MAPK pathways implicated in TGF- β 1 responses, c-Jun
349 N-terminal kinases (JNK) and ERK have been described for their activation in
350 fibrotic disease and involvement in the expression of fibrotic markers(3, 26, 31,
351 38, 42, 43, 55, 72). In the present study, areas of the mucosa of both WT and
352 PHD-2 \pm mice where α -SMA positive fibroblasts are concentrated exhibited
353 increased pERK nuclear staining, confirming the activation of the ERK pathway
354 in fibrotic colons (Figure 5A). In vitro, DMOG did not affect TGF- β 1 induced
355 phosphorylation of JNK (data not shown). In contrast, DMOG reduced TGF- β 1-
356 induced phosphorylation of ERK (pERK) at 8 hours post stimulation (Figure 5B
357 and 5D). Interestingly, DMOG did not affect the phosphorylation of the
358 upstream kinase MEK at the same time point, indicating that the kinase cascade
359 was specifically affected at the level of ERK activation (Figure 5C and 5E).
360 Phosphorylation of the linker region of Smad2, which is mediated directly by
361 ERK(11, 29, 69), was also moderately decreased by DMOG further confirming
362 the effects of DMOG on phosphorylation of ERK (Figure 5B). The hydroxylase
363 inhibitor JNJ1935 and atmospheric hypoxia were also examined for their effects
364 on ERK activation. JNJ1935 caused a time-dependent reduction in TGF- β 1-
365 induced ERK phosphorylation that was already present at 6 hours and was
366 profound at 8 hours post TGF stimulation (Figure 5F and 5G). Of note, hypoxia
367 did not significantly affect the ability of TGF- β 1 to activate this kinase cascade
368 (Figure 5F and 5G). In order to further analyse the mechanism of hydroxylase
369 inhibitor mediated reduction of ERK phosphorylation, we compared the effect

of DMOG and JNJ1935 on ERK and MEK phosphorylation to that of the MEK inhibitor PD184161 (Figure 5H). While DMOG and JNJ1935 reduced ERK phosphorylation without affecting that of MEK, the reduction of ERK phosphorylation caused by PD184161 was accompanied by a dramatic increase in phosphorylated MEK (Figure 5H). Taken together, these results show that hydroxylase inhibitors modulate TGF-ERK signalling, which is a potential mechanism whereby they exert anti-fibrotic effects.

6. The antifibrotic effect of hydroxylase inhibitors is independent of HIF

Our previous in vivo studies demonstrated no protective effects of PHD2 deficiency against fibrosis, thus providing evidence that the antifibrotic effects of DMOG are HIF independent. To further demonstrate this hypothesis, we compared the response of WT and PHD2^{+/-} MEF to TGF- β 1. Heterozygous deficiency of PHD2 did not block ERK phosphorylation in response to TGF- β 1, nor did it prevent the ability of DMOG or JNJ1935 to reduce levels of pERK (Figure 6A). Moreover, stimulation of PHD2^{+/-} cells with TGF- β 1 caused an increase in production of α -SMA and CTGF mRNA (Figure 6B and 6C). The increment was significantly higher than that found in WT cells, but was nevertheless abrogated when PHD2^{+/-} cells were treated with DMOG (Figure 6B and 6C). Next, we analysed whether reducing HIF in hydroxylase inhibitor treated cells would affect the ability of the compounds to reduce the expression of fibrotic markers. Drugs such as Digoxin and Camptothecin have been

described as potent HIF inhibitors (8, 46, 76). As has been previously described, we found treatment with either digoxin or camptothecin to reduce DMOG mediated HIF-1 α protein stabilization in MEF (data not shown). However, this reduction of HIF did not affect the ability of DMOG to reduce the expression of Acta2 (α -SMA) or Ctgf RNA (Figure 6D and 6E). Together these data suggest that the antifibrotic effects of hydroxylase inhibitors are independent of HIF.

Discussion

Hydroxylase inhibitors have recently been shown in clinical trials for anemia to be well tolerated by patients and therefore represent a potentially important new class of therapeutic agents(9, 28). We and others have previously demonstrated protective effects of these reagents in multiple models of murine colitis. Therefore, the potential for repurposing hydroxylase inhibitors for the treatment of colitis is a realistic possibility. Here, we investigated whether the beneficial effects of hydroxylase inhibition in intestinal inflammation extend to inflammation-associated fibrosis, using the DSS-induced murine colitis model. We show that treatment with the pan-hydroxylase inhibitor DMOG during the post-DSS recovery period reduces intestinal fibrosis in addition to its known anti-inflammatory effects. We also show that hydroxylase inhibitors are able to block TGF- β 1 mediated activation of intestinal fibroblasts as well as MEF, and that they do so at least in part via a HIF-independent manner. At the molecular level, the inhibitors reduce TGF- β 1 mediated activation of the ERK signalling pathway, thus providing mechanistic insight into the anti-fibrotic actions of these compounds.

The DSS model of colitis has been used to investigate intestinal fibrosis by allowing long recovery periods after exposure to DSS(63, 71). Another approach to the DSS colitis model often used to investigate fibrosis is the so called multicycle DSS model, where the animals are exposed to multiple cycles

429 of DSS followed by one week recovery periods. In a study comparing the
430 different approaches, Ding et al showed the presence of fibrosis already after
431 the first DSS cycle of DSS and highlighted that C57BL6 mice do not show
432 mucosal healing after DSS and progress towards chronic colitis(17). Moreover,
433 the notion that fibrosis is also a common complication in ulcerative colitis
434 further validates the potential for the DSS recovery model of colitis as a model
435 for the study of intestinal fibrosis(23). As previously described, our results show
436 that mice allowed to recover after exposure to DSS have evident signs of
437 inflammation and fibrosis even 8 or 14 days after DSS exposure. We also noted
438 that there are differences in disease progression between the different strains of
439 mice used. C57BL6 were susceptible to a lower dose of DSS and rapidly
440 developed colitis showing signs of disease already during the DSS exposure
441 period. In contrast, Swiss 129 mice did not show signs of disease initially, even
442 if exposed to a higher dose of DSS. However, this mice developed clear signs of
443 colitis after the DSS period and progressed towards more severe colitis and
444 fibrosis. In our studies, treatment of mice with DMOG during the post-DSS
445 recovery period reduced fibrosis as shown by the reduced presence of mucosal
446 α -SMA positive fibroblasts and reduced sub-mucosal collagen deposition.
447 These effects were associated with reduced inflammation, showing that
448 hydroxylase inhibitors might prove beneficial if used as treatments in
449 established colitis. Of note, a number of recent studies have indicated that the
450 inhibition of PHD2 positively regulates healing responses, supporting the

hypothesis that hydroxylases might be novel targets for the modulation of wound healing and therefore, fibrosis(32, 78, 80). In our studies, however, PHD2^{+/-} mice were not protected against chronic inflammation or fibrosis induced by DSS. Furthermore, PHD2^{+/-} MEF did not demonstrate reduced sensitivity to TGF- β 1 stimulation compared to WT, suggesting that the beneficial effects of hydroxylase inhibitors in wild-type mice are likely independent of the PHD2/HIF axis. This HIF independent mechanism is also supported by the antifibrotic effects obtained with JNJ1935, a drug used at a concentration that does not inhibit FIH and thus, does not strongly activate HIF. We further tested the involvement of HIF in hydroxylase inhibitor anti-fibrotic actions by inhibiting HIF stabilization in DMOG treated cells. As previously demonstrated, digoxin and camptothecin reduced HIF-1 α in DMOG treated cells(8, 46, 76). However, this did not affect the ability of DMOG to reduce the expression of α -SMA and CTGF in TGF- β 1 stimulated cells. This provided further evidence that the anti-fibrotic action of hydroxylase inhibitors is HIF independent.

Fibrosis results from overactive wound healing and is mainly attributed to the profibrogenic factor TGF- β 1(16, 42, 49, 67). In our studies, hydroxylase inhibitors demonstrated specific anti-fibrotic actions by targeting the ability of TGF- β 1 to up-regulate the production of various key fibrosis markers in cultures of human colonic fibroblasts and MEF. However, DMOG failed to

472 block the phosphorylation of Smad2/3 or the activation of a Smad luciferase
473 reporter in response to TGF- β 1. Rather, hydroxylase inhibitors reduced TGF- β 1
474 mediated activation of the ERK signalling pathway, which has been shown to
475 play important roles in fibrosis(31, 42, 55) and which we found to be active in
476 areas of intestinal fibrosis. Thus, we purpose that hydroxylase inhibitors target
477 the activation of the non-canonical TGF-ERK signaling pathway to cause the
478 inactivation of the ERK mediated fibrotic response (Figure 7). Together, these
479 results indicate that hydroxylase inhibitors, in addition to their previously
480 described anti-inflammatory effects, have beneficial effects against intestinal
481 fibrosis at least in part through inhibition of the TGF-ERK signaling pathway.
482 Of note, the inhibitory effects of hydroxylase inhibitors on ERK
483 phosphorylation were not seen for its upstream kinase MEK. Indeed,
484 comparison between hydroxylase inhibitors and a MEK inhibitor suggested a
485 different mechanism for the inhibition of ERK phosphorylation between the two
486 types of drugs. While MEK inhibitors reduced ERK phosphorylation but
487 induced a higher level of phosphoMEK, hydroxylase inhibitors reduced
488 phosphoERK but did not affect phosphoMEK. In order to gain further insights
489 to the possible mechanism of this PHD inhibitor mediated regulation of ERK
490 phosphorylation, we hypothesised that PHD inhibitors could upregulate dual
491 specificity phosphatases (DUSP). DUSP are known to inactivate MAPK and
492 have been shown to be regulated by hypoxia in multiple studies(5, 35, 41, 54,
493 56, 66). Hydroxylase inhibition did not increase the expression of DUSPs

investigated (data not shown). Furthermore, our results are in line with recently published reports showing beneficial effects of hydroxylase inhibitors in fibrosis(34, 57, 62, 73, 77). Of note, previous studies have described deleterious effects for HIF activation in fibrotic pathologies(27, 70). The current study is not in contradiction with this possibility, as we show that the intestinal antifibrotic actions of hydroxylase inhibitors are HIF-independent.

The ability of hydroxylase inhibitors to regulate the stability of HIF- α subunits may have not only beneficial effects, but also potential adverse effects. A widely discussed side effect of hydroxylase inhibitors is the activation of HIF-dependent EPO production(6, 30, 33), which is seen as an important limitation to the use of these drugs. However, this ability to increase EPO is currently being investigated as a therapy for anemia(6, 9, 28). In IBD, anemia is one of the most common extraintestinal symptoms and it is estimated that one third of IBD patients suffer from anemia(21). Moreover, anemia is reportedly predictive of severe and disabling progression in IBD(39). Therefore, the activation of EPO production with hydroxylase inhibition could be a secondary beneficial effect in IBD patients where fibrosis and anemia are often co-incidental outcomes. On the other hand, the use of targeted release forms that allow specific local delivery of hydroxylase inhibitors to the colon could minimize systemic exposure. In recent work, we demonstrated that the use of DMOG

mini-spheres formulated to target delivery to the colon achieved anti-inflammatory effects while minimizing systemic side effects(65).

IBD, including Crohn's disease (CD) and ulcerative colitis (UC), is increasing in prevalence, especially in developed countries(45, 51). Advanced stages of IBD are often associated with excessive wound healing causing fibrosis and tissue scarring. While much IBD research seeks to unravel the early causes of pathology, less attention has been paid to long-term complications. Despite the advances achieved in the treatment of IBD with novel therapies such as anti-TNF- α antibodies that help to maintain remission(14, 44), IBD is still in need of improved therapeutic approaches. Intestinal fibrosis is a major indication for surgery in IBD as 75-80% of CD patients are estimated to require surgical intervention due to the formation of fibrotic scars leading to intestinal obstructions(47, 59, 63). Further, the importance of fibrosis in a number of other chronic inflammatory diseases such as chronic kidney disease or interstitial pulmonary fibrosis(16, 18, 24, 59, 74) and the lack of effective means to limit progression towards fibrosis suggest that treatments which target fibrotic disease may represent an important therapeutic advance. We have shown that hydroxylase inhibitors have promising anti-fibrotic effects, potentially due to their actions on the non-canonical TGF-ERK signalling pathway.

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Author contributions

Mario Manresa, Murtaza Tambuwala, Jonathan Harnoss, Martin Schneider and Cormac Taylor participated in the design of this study. Mario Manresa, Murtaza Tambuwala, Praveen Radhakrishnan, Eric Brown, Miguel Cavadas, Ciara Keogh and Alex Cheong participated in the acquisition of data. Mario Manresa,

554 Murtaza Tambuwala, Eoin Cummins, Kim Barrett and Cormac Taylor
555 participated in the analysis and interpretation of the data. Mario Manresa, Kim
556 Barrett and Cormac Taylor participated in the drafting of this manuscript.

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Tables

Target	Supplier	Code
α-SMA	Abcam	Ab7817
Collagen-1(α)-1	Santa Cruz Biotechnology	sc-8784
HIF-1α	BD Transduction Laboratories	#610958
HIF-1α (clone H1a67)	Merck Millipore	MAB5382
pSmad2 (carboxyterminal)	Merck Millipore	AB3849
pSmad2 (linker)	Cell Signalling Technology	#3104
pSmad3	Cell Signalling Technology	#9520
TotalSmad2	Cell Signalling Technology	#3103
TotalSmad3	Cell Signalling Technology	#9513
pERK	Santa Cruz Biotechnology	sc-7383
TotalERK	Cell Signalling Technology	#9102
Alexa fluor 488 (anti-mouse)	Thermo Fisher Scientific	A-21202

Table 1. *Antibodies list.* List of antibodies used for immunostaining and western blot protein analysis.

Target	Sequence	Chemistry	Source
m-α-SMA (Acta2)	5'-TGCTGTCCCTCTATGCCTCT-3', sense		
	5'-GCAGGGCATAGCCCTCATAG-3', antisense	Sybr green	Self-designed
Ctgf	Commercially available Taqman probe	Taqman	Applied Biosystems
Eukaryotic 18S rRNA	Commercially available Taqman probe	Taqman	Applied Biosystems

Table 2. *Primer list.* List of target genes analysed and the complementary primers used for qRT-PCR. The list includes the source of the primers.

Figure legends

Figure 1. *DMOG reduces fibrosis in DSS induced colitis.* A, representative images of mouse colon stained with hematoxylin and eosin (H&E), Picrosirius red imaged with double polarized light (collagen) and immunofluorescence histochemistry (α -SMA). White arrows point areas of major collagen accumulation or α -SMA positive infiltrates. Quantification of disease activity index (DAI) (B), assessment of tissue inflammation (C), submucosal collagen deposition (D) and α -SMA positive infiltration (E). n=4, * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$.

Figure 2. *Heterozygous deficiency of PHD2 does not protect against intestinal fibrosis in DSS-induced colitis.* A, representative images of mouse colon from WT and PHD2 $^{+/-}$ mice stained with H&E, Picrosirius red imaged with transmitted light (collagen) and immunofluorescence histochemistry (α -SMA). Quantification of disease activity index (DAI) in WT mice comparing natural recovery to IP DMOG treatment (B); Quantification of DAI comparing natural recovery between WT and PHD2 $^{+/-}$ mice (C); Assessment of tissue inflammation (D); Quantification of α -SMA positive staining (E); Quantification of percentage of mucosal collagen (F). n \geq 3, * $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$.

Figure 3. *Hydroxylase inhibition reduces TGF- β 1 induced human colonic fibroblast activation.* A, representative images of CCD-18Co cells stimulated with 1ng/ml TGF- β 1 and stained for α -SMA using immunofluorescence histochemistry with DAPI as a nuclear counter-stain (n=2). B, representative western blot of α -SMA and collagen-1(α)-1 in CCD-18Co cells stimulated with 1ng/ml TGF- β 1 (n=3); C, representative images of CCD-18Co stimulated with 1ng/ml TGF- β 1 and treated with 1mM DMOG or 100 μ M JNJ1935, stained for α -SMA using immunofluorescence histochemistry with DAPI as a nuclear counter-stain (n=3). D, representative western blot of α -SMA and collagen-1(α)-1 in CCD-18Co cells treated with 1mM DMOG or 100 μ M JNJ1935 and stimulated with 1ng/ml of TGF- β 1 for 48 hours (n=10). E, densitometry of α -SMA in CCD18Co treated as described in D (n=10). F, densitometry of collagen-1 α in CCD18Co cells treated as described in D (n=10).

875
876 **Figure 4.** *Hydroxylase inhibition does not affect TGF- β 1 induced Smad activation.* A,
877 representative images of MEF monolayers, treated with 1mM DMOG for 1 hour, wounded
878 and then stimulated for 24 hours with 10ng/ml TGF- β 1, stained for α -SMA using
879 immunofluorescence histochemistry with DAPI as a nuclear counter-stain (n=4). B, qRT-
880 PCR of α -SMA in MEF stimulated with 1ng/ml TGF- β 1 and treated with 1mM DMOG
881 (n=3); C, representative western blot of pSmad2, pSmad3, TotalSmad2, TotalSmad3, HIF-1 α
882 and β -Actin in MEF stimulated with 1ng/ml TGF- β 1 for 1/2h or 1h or 2h and treated with
883 1mM DMOG for 1h +/- 1/2h 10nM MG132 pre-treatment (n=6); D, densitometry of pSmad2
884 (n=6); E, densitometry of pSmad 3 (n=6). F, luciferase production in MEF transfected with
885 SBE4-Luc and co-transfected with pCMV5B-Smad3-flag or pCMV5-Smad2-HA (n=4); G,
886 luciferase production in MEF transfected with SBE4-Luc and stimulated with 1ng/ml TGF-
887 β 1 and treated with 1mM DMOG (n=4). * p \leq 0.05; ** p \leq 0.01; *** p \leq 0.001.

888 **Figure 5.** *Hydroxylase inhibition reduces TGF- β 1 induced ERK activation.* A, representative images
889 of mouse colon cross-sections stained for α -SMA using immunofluorescence histochemistry and
890 stained for phospho-ERK (pERK) using immunohistochemistry (n \geq 3). Red arrows point areas of
891 abundant pERK positive cells, which are often coincident to areas where activated fibroblasts
892 accumulate. B, representative western blot of pERK, TotalERK, pSmad2 linker, TotalSmad2 and β -
893 Actin in MEF stimulated with 1ng/ml TGF- β 1 and treated with 1mM DMOG (n=6); C,
894 representative western blot of pMEK and β -Actin in MEF stimulated with 1ng/ml TGF- β 1 and
895 treated with 1mM DMOG (n=5). D, densitometry for pERK of the western blots described in B
896 (n=6); E, densitometry for pMEK of the western blots described in C (n=5). F, representative
897 western blot of pERK, TotalERK, pMEK, TotalMEK and β -Actin in MEF stimulated with 1ng/ml
898 TGF- β 1 and treated with 100 μ M JNJ1935 or 1% oxygen (n \geq 3); G, densitometry for pERK of the
899 western blots described in F; H, representative western blot of pSmad2 linker, pERK, pMEK and β -
900 Actin in MEF treated with 1mM DMOG or 100 μ M JNJ1935 or 0.3mM PD184161 and stimulated
901 with 1ng/ml of TGF- β 1 (n=4). * p \leq 0.05; ** p \leq 0.01.

Figure 6. *The anti-fibrotic effect of hydroxylase inhibitors is HIF independent.* A, representative western blot of pERK, TotalERK and β -Actin in WT vs PHD2^{+/-} MEF stimulated with 1ng/ml TGF- β 1 and treated with 1mM DMOG or 100 μ M JNJ1935 (n=4); qRT-PCR of α -SMA (B) and CTGF (C) in WT vs PHD2^{+/-} MEF stimulated with 1ng/ml TGF- β 1 and treated with 1mM DMOG (n \geq 3). Quantitative real time PCR of α -SMA (D) or CTGF (E) in MEF pre-treated with 100 μ M digoxin or 2 μ M camptothecin for 30 minutes, then with 1mM DMOG for 1 hour and then stimulated with 1ng/ml TGF- β 1 for 8 hours (n \geq 3). * p \leq 0.05; ** p \leq 0.01.

Figure 7. *Purposed mechanism for hydroxylase inhibitor mediated anti-fibrotic actions.* Upper panel displays the combination of TGF- β 1 activated Smad dependent (canonical) and non-canonical (ERK dependent) signaling pathways. Lower panel shows our purposed model for hydroxylase inhibition antifibrotic action. Pharmacologic inhibition of oxygen sensing hydroxylases mediates the long term dephosphorylation of the non-canonical TGF-ERK signaling pathway and reduces the crosstalk between ERK and Smad pathways. This causes a reduction of the TGF mediated fibroblast activation and ameliorates fibrosis in a mouse model of colitis.

Figure 1

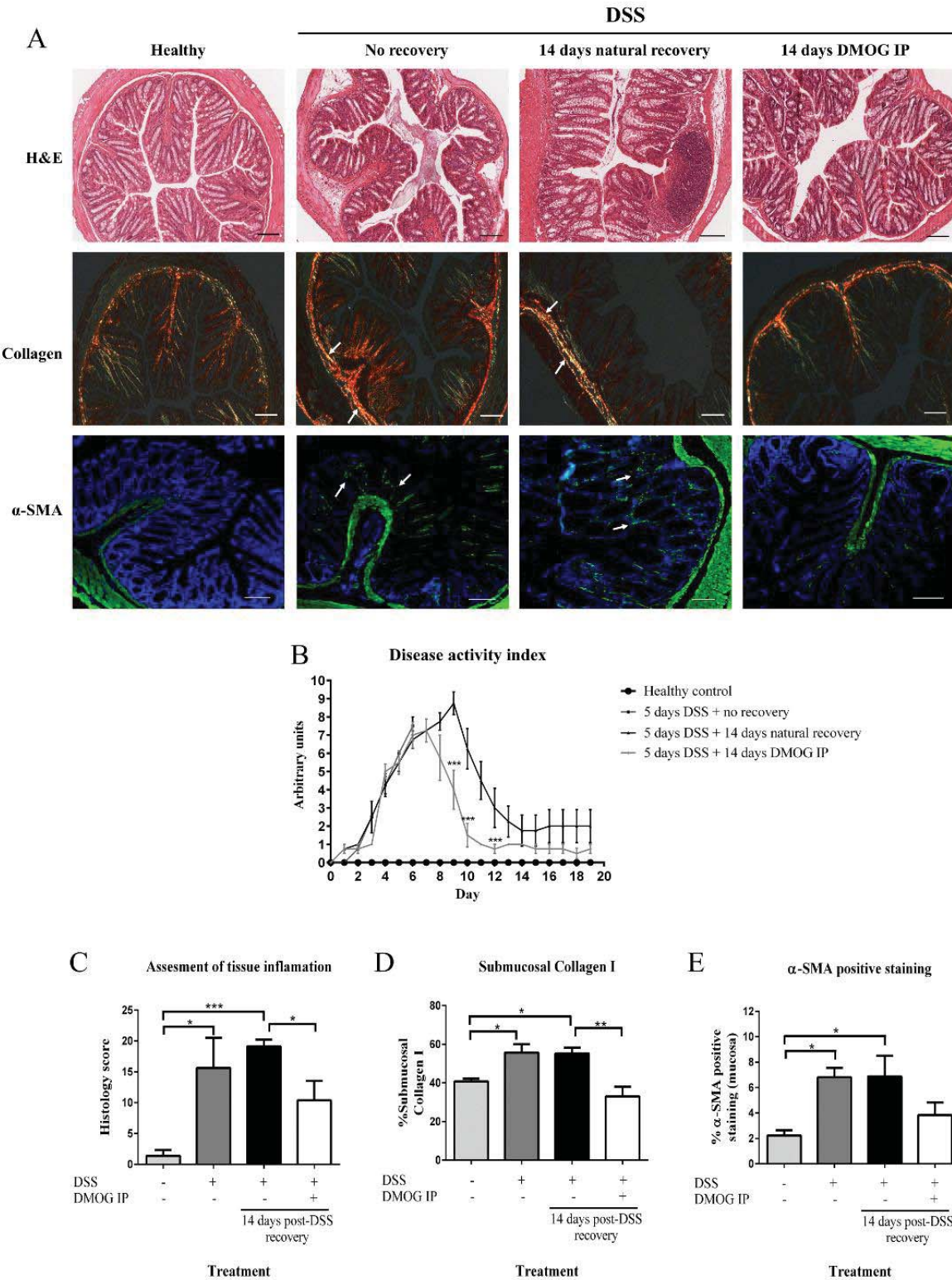


Figure 2

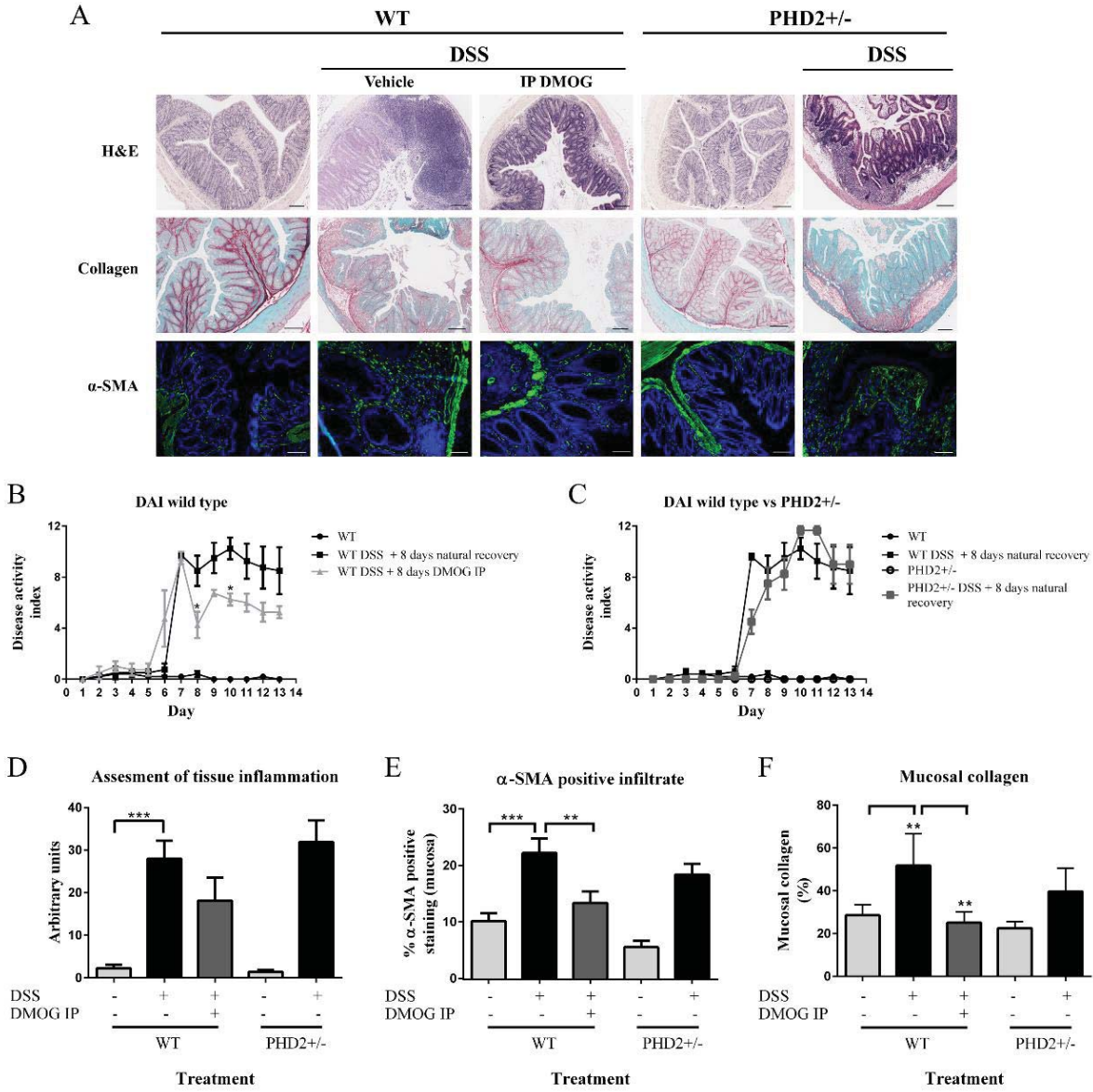
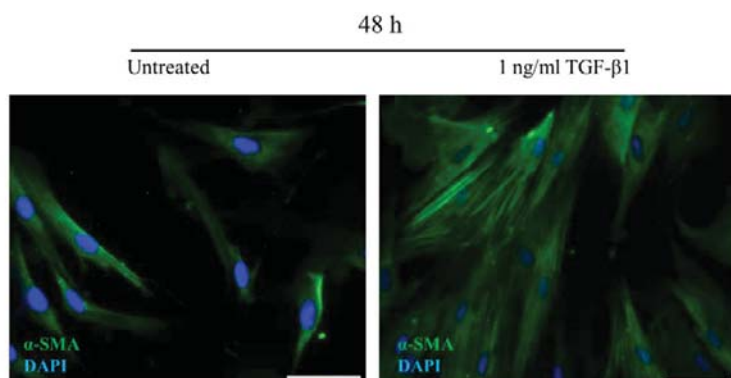
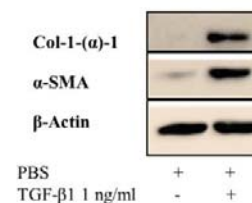


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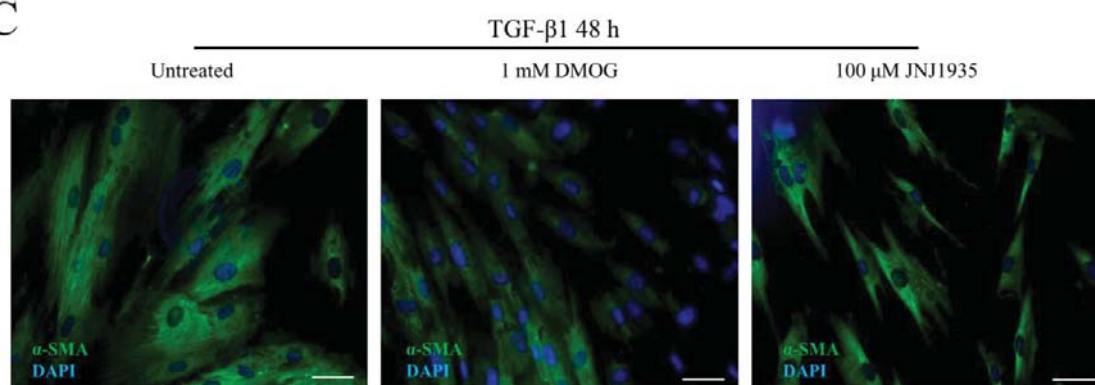
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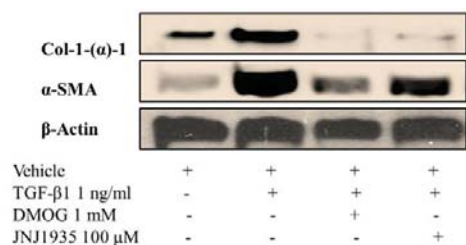
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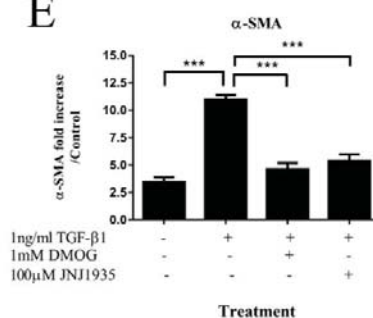
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D



E



F

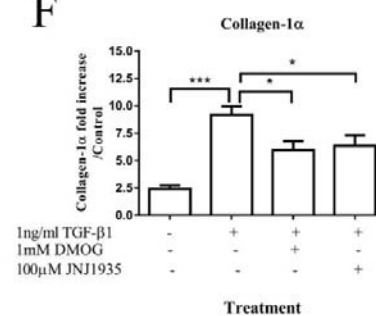


Figure 4

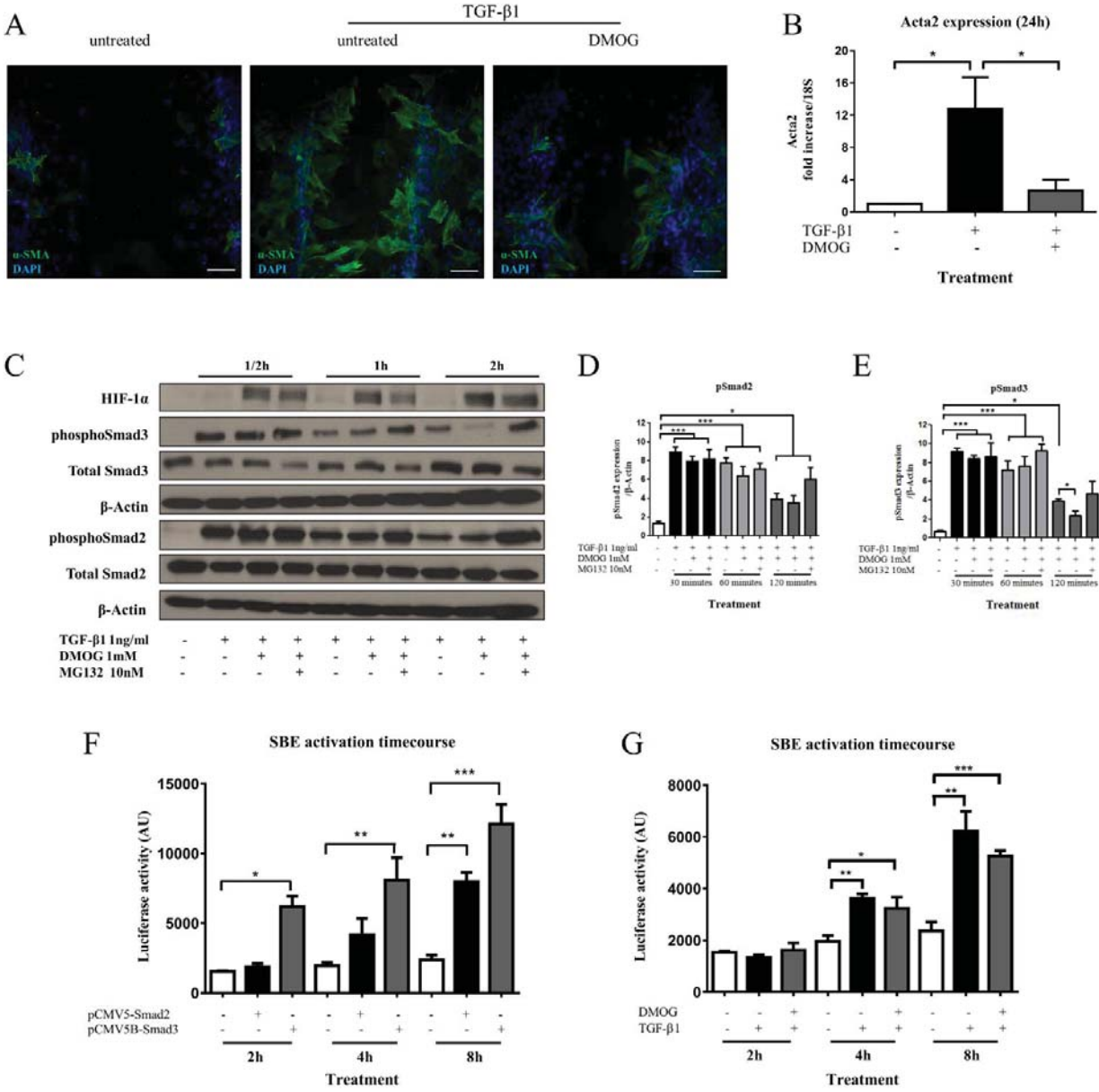


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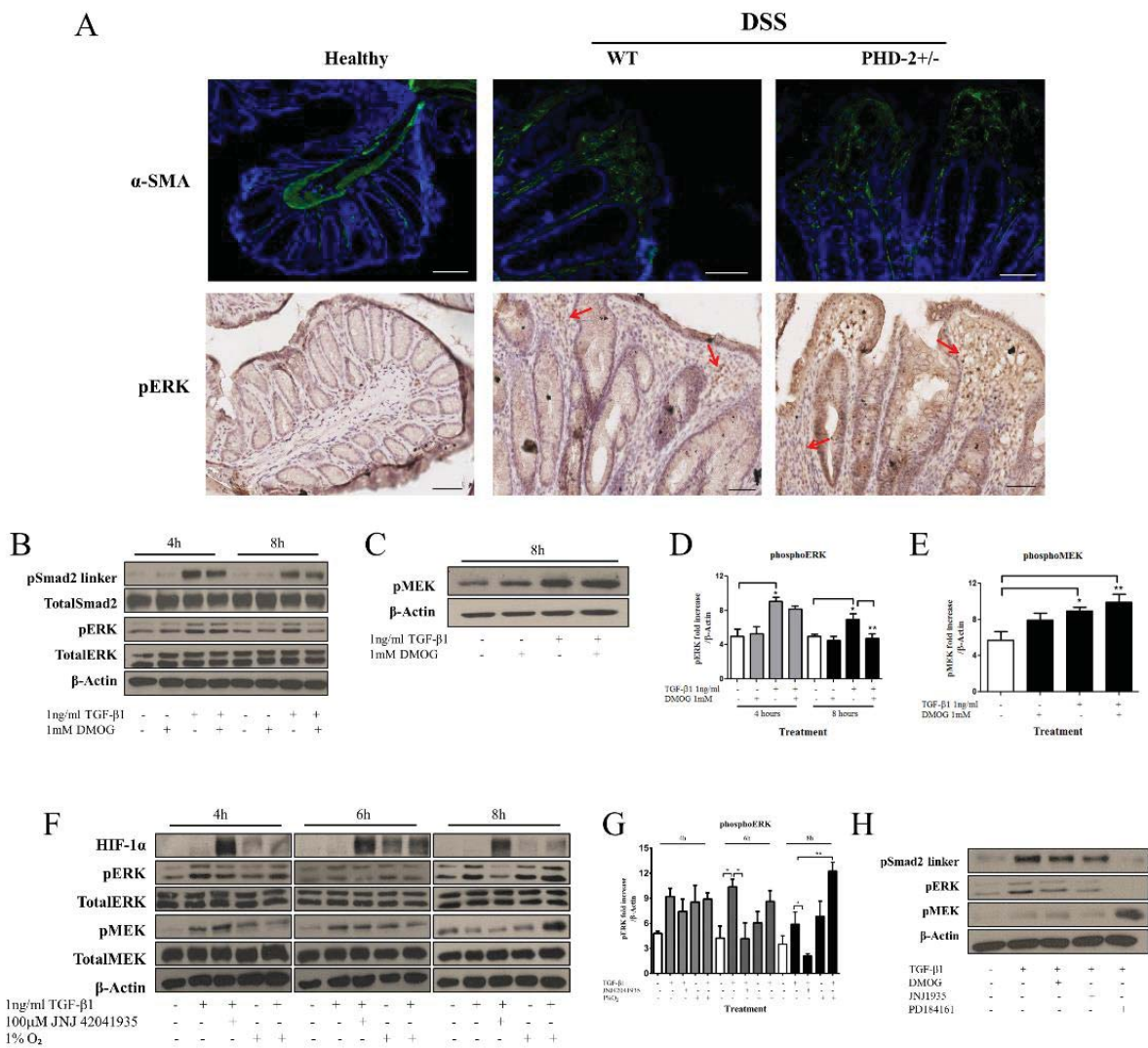


Figure 6

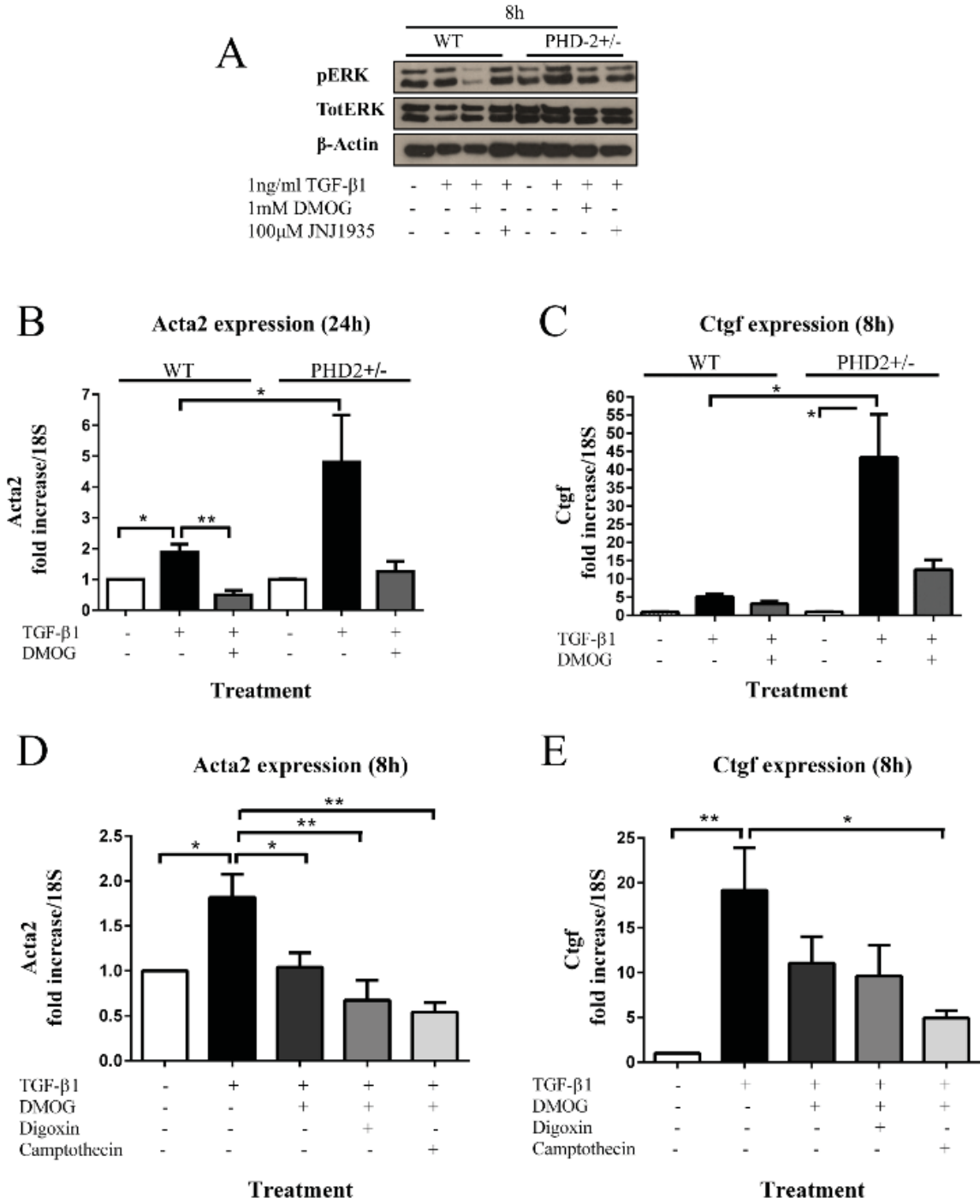


Figure 7

